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AD No. 404286

QUARTERLY PROGRESS REPORT

EXPLOSIVE FORMING OF CLOSURES FOR LARGE
SOLID PROPELLANT MOTOR CASES

Report 0665-01(04)QP

17 January 1963 - 17 April 1963

Contract No. AF 04(611)-8395

ORDNANCE DIVISION

Aerojet-General
CORPORATION

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY
AZUSA, SACRAMENTO, AND DOWNEY, CALIFORNIA

(4)
$5.60

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(6) EXPLOSIVE FORMING OF CLOSURES FOR LARGE SOLID PROPELLANT MOTOR CASES

(7+8) NA

(9) Quarterly Progress Report No. 4,
(14) ~~Report~~ 0665-01-(04)QP
(17 January 1963 - 17 April 1963)

Edwards Air Force Base
Edwards, California

(15) Contract ~~No~~. AF 04(611)-8395
Air Force Program Structure No. 623A
AFSC Project No. (Not Applicable)
AFSC Task No. (Not Applicable)

(11) 30 April 1963
(12) 10

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ABSTRACT

The contour of an explosively formed closure is affected by the charge configuration. Design of the charge shape to give optimum reproducible closure contour would eliminate many problems in the fabrication of large size rocket closures. The initial results of closure contours as affected by variations in explosive configuration are presented in this report. Formability of 18% nickel maraging steel and the weldability of this material by explosive pressures are also briefly described herein.

FOREWORD

This Quarterly Progress Report covers the work performed from 17 January 1963 through 17 April 1963 under Contract No. AF 04(611)-8395, under the cognizance of the 6593d Test Group (Development), Code DGSCH, Edwards Air Force Base, Edwards, California. This contract is under the technical direction of Lt. B. Thomas of the 6593d Test Group.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont.)

1. INTRODUCTION

The original objective of this program was the demonstration of the feasibility of the free-forming approach or the ice die approach to produce two 120-inch diameter rocket motor closures by the explosive forming process. However, it has been mutually agreed with the Air Force Contracting Officer to redirect the effort for the period remaining under this contract to perform in the following areas:

a. To determine the capabilities of the explosive charge shape and orientation to be used as the control for producing a given head contour and configuration. This will permit the utilization of, basically, a die-less forming technique which would have application to the solution for producing larger rocket motor components.

b. An investigation to determine the minimum stress-relief or anneal that is necessary on welded blanks to permit full deformation without weld failure. This study is of value where the large furnace facilities are at a premium or are practically non-existent at the higher temperatures required for the annealing, particularly where atmosphere control is necessary. Thus, if no post weld heat-treatment, or a minimum post weld heat-treatment, can be shown as practical, a serious problem in finding adequate furnace facilities may be eliminated.

c. A modest effort to be expended in the investigation of the formability by explosive pressures of 18% nickel steel and the behavior of this material when explosive welding techniques are applied.

2. WORK SUMMARY

The implementation for the redirection of the program was started late in this period, and the original planning was carried out during the major portion of this three months' period.

2.1 Two AMS 6434 steel blanks, 185 inches in diameter, were contour-machined to a thickness pattern calculated to yield a uniform thickness in the formed dome. However, due to excessive waviness in the sheet material and to the effects of the residual stresses which became very pronounced as machining proceeded, it was not possible to machine the blanks as originally planned. Variations as large as $\pm$ .040-inch from specified thickness in the range of .180-inch did not allow for experimentation to be carried out per original schedule.

2.2 Major weld repairs on the 120-inch diameter die were necessary due to fracture and failure of weld areas as well as parent material. These failures were the result of the ductile-brittle transition for the AISI 1020 die material when ice was used. The repairs consumed considerable time and very clearly demonstrated the need for a different die material when the ice die approach is to be utilized. The die currently is in good repair and may be used as a full-scale free-forming die.

2.3 The hemispherical plaster mold fractured due to absorption of water, subsequent freeze-up and eventual weakening of the structure. The mold was repaired and several layers of glass cloth and plastic resin laminate were applied on the O. D. to increase impermeability of the surface to the water. This improved mold, shown in Figure 1, is being held pending any requirements for a hemispherical mold configuration.

2.4 To overcome the overforming observed in the knuckle area of a head when the blank is formed in a free-forming die, a 6-inch long contoured cylindrical insert was fabricated and welded in the mouth area of the 36-inch subscale die in an attempt to guide the metal during forming and prevent overforming in the knuckle area. Although markings in the formed head showed that there was contact between the head and insert, nevertheless, overforming did occur in an area below the level covered by the contoured insert. The approach using direct mechanical restraint to maintain a contour does not appear to be the solution for as this restraint is extended further, it will eventually end up in a complete, or almost complete, solid cavity die.

2.5 Six 58-inch diameter AISI 4340 steel blanks, 1/4-inch thick, have been cut through one diameter and rejoined by welding, using the tungsten-inert gas method (TIG) in preparation for the study on the degree of stress-relief or anneal that is required to prevent failure in the weld during explosive forming. This study is of particular interest when extended to the large 158-inch closures as annealing furnaces are not readily available for this size. The first plate has been stress relieved at 1200°F for one hour and will be tested.

2.6 Repeated fractures and repairs of the 36-inch die during its use as an ice die have made it increasingly difficult to produce closures that are not affected by weaknesses in the repaired areas. A redesigned 36-inch free forming die was fabricated in AISI 4130 steel, which will assist in better controlling the test conditions. The die shown in Figures 2 and 3 is now in use.

2.7 Fourteen 58-inch diameter blanks are in process of being cut from the two 3/4-inch thick AMS 6434 steel blanks, 185 inches in diameter. Seven small blanks can be obtained from each blank. These blanks will be contour-machined to produce a uniform thickness in the formed closure and will be formed after results from the charge shaping study are tabulated and analyzed.

2.8 Eighteen per cent nickel steel specimens, 3/8-inch and .175-inch thick, were explosively formed. The material does not form as readily as AMS 6434 and there is an apparent tendency for the blank to fracture. Reasons for this tendency in this material will be examined further.

2.9 A detailed study is being made of the contour produced in the full-scale dome F-1, and a complete report on the symmetry and regularity of contour is in process of preparation for presentation in the final report.

2.10 Explosive welding techniques were applied to the 18% nickel steel and the results obtained as examined structurally are very encouraging. An evaluation of the mechanical strength of the bond will be made.

3. TECHNICAL DISCUSSION

A tabulation of test firings completed during this period, listing the test conditions and the results obtained, is presented in Table I.

A total of twenty-five tests were completed; thirteen of these were 18% nickel steel tests using both a 13-inch diameter and a 6-inch diameter die, eleven tests were performed with the subscale 36-inch diameter die, and one test was in the full-scale 120-inch free forming die.

3.1 120-INCH DIAMETER TEST FIRING

One full-scale firing was performed in the 120-inch diameter free forming die. The thickness of an AMS 6434 blank was machined to produce a uniform thickness of .150-inch when formed in a hemisphere. However, because of machining difficulties previously described, variations as much as .040-inch from the specified thickness were obtained. A sandwich plate of AISI 1020 steel, 3/8-inch thick, was used to prevent wrinkling of the closure.

3.1.1 The standoff between the explosive charge and the plate was set at 11 inches. This value was established as the minimum that would permit maximum deflection without detrimental effects to the blank. It was not possible to increase the standoff and compensate for this by increasing the explosive charge since the maximum charge established for the tank was being used.

3.1.2 The sandwich plate and workpiece both fractured during the forming process, and only partial forming was achieved in Test F-4. Extreme thinout was observed in the apex area of the formed part. Excessive thinning leading to fracture resulted from the acceleration of the steel in the apex region. Table II presents the thickness data for F-4 before and after forming. Thickness change is plotted in Figure 4.

3.1.3 It was as a result of this test that the problem area relative to the inability to machine the 3/4-inch thick blanks to a useful thickness ($\sim$ .150 to .250-inch thickness) due to the waviness in the blank, led to the necessity to redirect the study from the full-scale to one on a subscale level. A contributing factor to the decision to go subscale only was the inability to increase the explosive charge much beyond the 30-lbs being used without endangering the available facilities.

3.2 TESTS TO RESTRAIN OVERFORMING

Tests shown in Table I as HS 1/4-6 through HS1/4-8 were fired to restrain the overforming observed in the knuckle area of the closure when it is formed in a free forming die. A contoured steel guide ring was welded concentric to the mouth of the die to serve as a restraint to the blank material as it tended to overform. The results from these tests showed no improvement, and further examination of this approach was abandoned for the moment since any attempts to improve on the restraining ring would approach the fabrication of a full cavity die, which is contrary to the main objective defined for the program.

3.3 EXPLOSIVE CHARGE CONFIGURATIONS IN OLD DIE

Two free forming tests were made in the mild steel, 36-inch diameter die: Test No. HS 1/4-11 used a flat disc explosive charge, 3-1/2-inch high x 10-inch diameter; Test No. HS 1/4-10 used a solid cylinder of explosive, 10-1/2-inch high x 4-1/2-inch diameter. Both charges had the same weight but with a 7-inch standoff for the cylindrical charge and a 10-inch standoff for the disc charge. Standoff is measured from the bottom of the charge to the testpiece. The 10-inch standoff was used to eliminate fracturing which occurred in HS 1/4-9, while obtaining comparable deflection in order to make contour comparisons. If the standoff distance is taken from the center of the charge to the workpiece, the standoff for both tests is approximately 12 inches.

3.3.1 A plot of the contours obtained for HS 1/4-10 and HS 1/4-11 is shown in Figure 5, and it is noted that despite the wide divergence in the explosive shape, the contour produced is essentially the same. However, the deflection was relatively small compared to a hemisphere, as this was only equivalent to an approximate 1.3:1 ellipse. One additional pancake charge was fired (HS 1/4-12) under test conditions equivalent to HS 1/4-9 and formed without fracture. The additional depth of part may be ascribed to the smaller standoff as compared to HS 1/4-10 and HS 1/4-11 when measured from the center of the charge length. Figure 6 illustrates the contour of the closure obtained in HS 1/4-12. When this contour is superimposed on the contours shown in Figure 5, with coincident apieces, the contours are essentially identical and the increase in deflection is reflected in the longer straight skirt section at the mouth. This type of contour behavior will be closely watched, as it may be significant that any improvements in deflection may not reflect themselves in an improvement of the contour.

3.4 EXPLOSIVE CHARGE CONFIGURATIONS IN NEW DIE

Three explosive charge configurations were fired in four tests in the new AISI 4130 steel die. The blanks were AISI 4340 steel, recently received, all from one lot. Charge weight in all tests was 2750 gms. Standoff as measured from the bottom of the charge to the workpiece was 7 inches. The three configurations were: spherical, pancake, and torus-shaped. The spherical charge was a standard spherical flask most frequently used in explosive forming. The pancake charge was 18-inch in diameter by 1/2-inch high. The torus charge was 27 inches in diameter measured across the O.D. of a coiled 1-1/2-inch diameter plastic tube, 85 inches long.

3.4.1 The three closures obtained from the sphere, pancake and torus charges are shown in Figures 7, 8, and 9 respectively. A contour comparison is shown in Figure 10 as taken from the data recorded on Table III. Strain and thickness data from these tests are shown in Figures 11 and 12 as plotted from Tables IV and V.

3.4.2 Examining Figures 11 and 12, it is noted that while the deflection for the torus charge was the smallest, the thinning at the apex was the greatest, and the thickening in the periphery was the least for the torus as compared to the other two configurations. This may be explained by the high acceleration imparted to the blank at the apex by the mach effect resulting from the shock meeting in the vicinity of the apex. This will cause considerable thinout, while the extent to which the blank is pulled in from the periphery is reduced, and is reflected by the smallest changes observed for the torus experiment in the peripheral areas of the blank. Figure 9 describes the conical shape obtained by the torus charge. The fractured portion in the apex is noted at the rear of the closure in Figure 9.

3.4.3 Of the three charge configurations, these preliminary tests would appear to indicate that the spherical charge will best approach the spherical contour in the formed dome. However, the degree of overforming is greater than for the torus and appears to be equal to the overforming shown by the pancake charge.

3.4.4 A second test firing of the torus charge (Test 4340-4) was made under conditions identical to Test 4340-3 to verify that the conical shape is reproduced by this explosive configuration. The blank behaved in the manner described above and fractured through the apex. Thickness and strain measurements confirm the data presented for Test 4340-3.

3.4.5 Figures 13 and 14 show the torus charge assembly and the die completely assembled with the explosive ready for lowering into the forming tank.

3.5 EXPLOSIVE FORMING 18% NICKEL STEEL

Eighteen per cent nickel steel specimens were obtained from United States Steel and Allegheny Ludlum in 3/8-inch thickness and .175-inch thickness respectively. The material was furnished annealed with chemical properties as shown in Table VI.

3.5.1 The first test piece was 11-3/4 inches in diameter and formed in a steel 13-inch diameter hemispherical die to a depth of 1-5/8 inches. This was formed without the material being drawn over a draw ring or being restrained between draw and hold-down rings. The net result is shown in Figure 15 where the material in the apex apparently did not form fully into the die due to resistance of the compressed air behind the blank, as no vacuum was drawn in the die. Using this approach, elongations measured were so small ($\sim$ 3% maximum) that it was considered desirable to form the material over a draw radius to introduce larger strains and greater elongations.

3.5.2 An available 6-inch diameter die with a draw ring radius of 1/2-inch was used to form USS-2 and USS-3, which were 3/8-inch thick blanks. The blanks sheared in the draw ring due to insufficient draw radius. The resulting domes are shown in Figure 16. The shearing apparently occurred early in the forming and the slug formed subsequent to shear. The depth of the dome so formed was approximately 2-1/4 inches. The radial fracture in the periphery as seen in Figure 15 apparently is due to compressive forces which develop as the slug is forced into the die cavity and instead of wrinkling, the material fractured. The die was modified to yield a 1-inch radius on the draw, and USS-4 and USS-5 were fired. In both cases, even with reduced deflection, shear in the draw radius was experienced. The behavior of other high strength steel will be examined in the equivalent assembly for comparison.

3.5.3 In the modified die with the 1-inch draw radius, the .175-inch thick material supplied by Allegheny Ludlum was tested. Figures 17 and 18 show side view and front view of domes formed in tests No. ALS-3, ALS-4 and ALS-5. Representative strain measurements and thickness changes are shown in Figures 19 and 20, taken from data tabulated in Tables VII and VIII. Examining the results shown in Table I for Tests ALS-1 through ALS-6, the following observations appear warranted:

a. There is an apparent inconsistency in the response of the material to the explosive forces to which it is subjected. With reduced explosive charges, greater deflection is achieved, i.e., ALS-3 versus ALS-4.

b. Fractures which do occur are not the typical type of radial fracture through the apex which is normally experienced with other steels, i.e., ALS-2 and ALS-6 shown in Figure 21. The random orientation of the fracture pattern may be related to the rolling direction, but has not been correlated until the material can be examined microscopically.

c. Little change in hardness of the material is observed as a result of forming. The changes that were noted indicate a decrease in hardness rather than an increase as would normally be expected. An average of ten readings for United States Steel as-received was R_C 32. Two formed domes of this material gave hardness averages of R_C 29.5 and R_C 31. The Allegheny Ludlum material as-received averaged R_C33.5, while two formed domes gave an average hardness of R_C 29 and R_C 30. The net result would indicate that working the material did not reflect itself in any increase in hardness.

3.5.4 Photomicrographs of the structures of the Allegheny Ludlum and United States Steel were made both in the as-received and in the explosive formed material. These photomicrographs are shown in Figures 22 through 25. While these are the first figures to be obtained, additional examinations are being planned to determine any structural changes that may have been introduced.

3.6 EXPLOSIVE WELDING APPLIED TO THE 18% NICKEL STEEL

3.6.1 The explosive welding test assembly for testing specimens .175-inch thick, 4-inch square of 18% nickel steel, is shown in

Figure 26. The test specimens were adjusted to an angle of 4^{o} with a standoff of .102-inch. Twelve gms per square-inch of sheet PETN explosive and steel buffer and anvil plates, 6-inch x 6-inch x 1/2-inch thick, were used.

3.6.2 A photomicrograph of the bond obtained between the two specimens is shown in Figure 27. The proximity of the surface areas is obvious even at the 500X magnification. However, the phase change in the material that is apparent from the photomicrograph must be examined further by X-ray diffraction and the bond itself evaluated for mechanical strength.

4. FUTURE WORK

4.1 Tests will continue to explore explosive charge shapes to control the contour of the formed closure. All 36-inch firings will be with high strength alloy steel blanks. When elliptical and/or hemispherical contours are successfully produced by the use of a controlled shock front, the procedure will then be scaled up to the fabrication of a full-scale head where time permits.

4.2 Preparations for the welded blank investigation are in process to establish the minimum post-weld heat-treatment necessary to permit a welded blank to be explosively formed into a head. The weld area through the apex of the blank is subjected to the highest strain during forming; therefore, tests will be conducted with welds through a diameter. The lowest stress relief cycle which proves satisfactory will be repeated to demonstrate reliability. The first plate has been stress-relieved at 1200°F for one hour, as large furnaces capable of maintaining 1200°F are readily available. Other plates will receive either a higher or lower stress-relief pending results of the first firing.

4.3 Study will continue with 18% nickel maraging steel to determine the maximum amount of elongation and strain that can be applied without detriment to the formed material. The program will, of necessity, be confined by the availability of material being furnished to Aerojet by the mills.

4.4 Further examination of the material in the weld zone of the explosively welded 18% nickel steel and evaluation of the strength of the joint will be made.

TABLE I

TABULATION OF TEST CONDITIONS AND RESULTS

Test No.	Type of Die	Die Condition	Material (Steel)	Firing No.	Explosive Charge (gms)	Standoff (in.)	Nominal Thickness (in.)	Defl. (in.)	Remarks
USS-1	13-inch Diameter	Steel Contoured	18% Nickel	1st	700	8	3/8	3/4	Hump in apex.
USS-1				2nd	350	6	3/8	1-5/8	Slight hump in apex.
USS-2	6-inch Diameter			1st	700	6	3/8	2-1/4	Sheared at draw radius.
USS-3				1st	466	8	3/8	2-1/8	Sheared at draw radius.
USS-4				1st	350	8	3/8	1-1/32	Slight fracture at draw radius.
USS-5				1st	466	8	3/8	1-3/8	170° fracture at draw radius.
ALS-1				1st	290	8	.175	1-5/8	Will refire.
ALS-1				2nd	290	8	.175	--	Fractured.
ALS-2				1st	466	8	.175	~2-3/4	Fractured.
ALS-3				1st	435	8	.175	2-3/8	Dome canted to one side.
ALS-4				1st	466	8	.175	2	Uniform dome.
ALS-5				1st	580	8	.175	2-5/16	Uniform dome.
ALS-6				1st	580	8	.175	--	Fractured.
HS 1/4-6	36-inch Diameter	Free Form	AMS 6434	1st	3,300	7-1/2	1/4	--	6-inch contoured ring at top of die - fractured.
HS 1/4-7				1st	2,750	7-1/2	1/4	18	6-inch contoured ring - overformed in knuckle area.
HS 1/4-8				1st	2,860	7	1/4	19-1/2	6-inch contoured ring - overformed in knuckle area.
HS 1/4-9				1st	2,750	7	1/4	--	Pancake charge 9-inch dia. x 5-1/2-inch - fractured.
HS 1/4-10				1st	2,750	7	1/4	14-1/2	Cylinder charge 4-1/2-inch dia. x 10-1/2-inch - slightly overformed in knuckle area.
HS 1/4-11				1st	2,750	10	1/4	14-1/4	Pancake charge 10-inch dia. x 3-1/2 inch - nipple in apex.
HS 1/4-12				1st	2,750	7	1/4	17-1/4	Pancake charge 10-inch dia. x 3-1/2-inch - slightly overformed in knuckle area.

TABLE I (Cont.)

TABULATION OF TEST CONDITIONS AND RESULTS

Test No.	Type of Die	Die Condition	Material (Steel)	Firing No.	Explosive Charge (gms)	Standoff (in.)	Nominal Thickness (in.)	Defl. (in.)	Remarks
4340-1	36-inch Diameter (A)	Free Form	4340	1st	2,750	7	1/4	21	Charge shape - sphere, overformed in knuckle area.
4340-2				1st	2,750	7	1/4	19-1/2	Pancake charge 18-inch dia. x 1/2-inch - overformed in knuckle area.
4340-3				1st	2,750	7	1/4	17-11/16	Charge shape - torus, split in apex.
4340-4				1st	2,750	7	1/4	--	Charge shape - torus, split in three sections from apex.
F-4	120-inch Diameter	Free Form	AMS 6434	1st	13,337	11	.150	--	Fractured.

TABLE II

THICKNESS MEASUREMENT DATA FOR 120-INCH DIAMETER FULL SCALE FIRING, F-4 *

Distance from Apex (in.)	Thickness Before Firing			Thickness After Firing			Thickness Change (in.)	% Change
	12 o'clock Radius (in.)	6 o'clock Radius (in.)	Average (in.)	12 o'clock Radius (in.)	6 o'clock Radius (in.)	Average (in.)		
0	.205	.205	.205	.095	.095	.095	.110	53.7
10	.169	.166	.168	.136	.136	.136	.032	19.0
20	.175	.175	.175	.147	.143	.145	.030	17.1
30	.188	.188	.188	.172	.152	.162	.026	13.8
40	.182	.182	.182	.175	.177	.176	.006	3.3
50	.177	.176	.177	.172	.175	.174	.003	1.7
60	.171	.169	.170	.168	.171	.170	.000	0
70	.160	.162	.161	.164	.167	.166	+.005	3.1
80	.136	.127	.132	.162	.161	.162	+.030	22.7
90	.338	.260	.299	.361	.291	.335	+.036	12.4

* Fractured through apex.

TABLE III

CONTOUR MEASUREMENT DATA ON CLOSURES FORMED FROM THREE CHARGE CONFIGURATIONS

Distance from Apex (in.)	Spherical Charge (in.)	Pancake Charge (in.)	Torus Charge (in.)
0	21	19-1/2	17-11/16
1	20-7/8	19-11/32	17-13/32
2	20-3/4	19-5/32	17-1/4
3	20-14/32	18-25/32	16-15/16
4	20-1/2	18-5/8	16-19/32
5	20-3/32	18-11/32	16
6	19-13/16	18	15-13/32
7	19-17/32	17-21/32	14-23/32
8	19-5/32	17-9/32	13-31/32
9	18-25/32	16-27/32	13-1/8
10	18-5/16	16-3/8	12-7/32
11	17-23/32	15-13/16	11-1/4
12	17	15-5/32	10-9/32
12-1/2	16-9/16	--	--
13	16-1/8	14-3/8	9-1/4
13-1/2	15-21/32	13-29/32	--
14	15-1/16	13-11/32	8-1/8
14-1/2	14-13/32	12-3/4	--
15	13-11/16	12-1/8	6-7/8
15-1/2	12-7/8	11-11/32	--
16	11-15/16	10-1/2	5-3/8
16-1/2	10-25/32	9-19/32	4-7/16
17	9-11/32	8-1/2	3-7/32
17-1/2	5-9/16	6-25/32	1-3/4
18	29/32	1-7/16	3/4

TABLE IV

STRAIN MEASUREMENT DATA ON THREE CHARGE CONFIGURATIONS

4340-1 SPHERICAL CHARGE						
	RADIAL			TANGENTIAL		
Distance from Apex (in.)	Average (in.)	Amount of Change (in.)	% Change	Average (in.)	Amount of Change (in.)	% Change
0	4.56	.56	14.0	4.57	.57	14.2
4	4.58	.58	14.5	4.53	.53	13.2
8	4.61	.61	15.2	4.44	.44	11.0
12	4.50	.50	12.5	4.26	.26	6.5
16	4.80	.80	20.0	3.92	-.08	-2.0
20	5.14	1.14	28.0	3.50	-.50	-12.5
24	4.82	.82	20.5	2.98	-1.02	-25.5
28	--	--	--	2.88	-1.12	-28.0

4340-2 PANCAKE CHARGE						
	RADIAL			TANGENTIAL		
Distance from Apex (in.)	Average (in.)	Amount of Change (in.)	% Change	Average (in.)	Amount of Change (in.)	% Change
0	4.75	.75	18.7	4.68	.68	17.0
4	4.52	.52	13.0	4.49	.49	12.2
8	4.41	.41	10.2	4.35	.35	8.8
12	4.42	.42	10.5	4.16	.16	4.0
16	4.76	.76	19.0	3.85	-.15	-3.7
20	5.07	1.07	26.8	3.33	-.67	-16.7
24	4.65	.65	16.2	2.98	-1.02	-25.5
28	--	--	--	3.12	-.88	-22.0

4340-3 TORUS CHARGE						
	RADIAL			TANGENTIAL		
Distance from Apex (in.)	Average (in.)	Amount of Change (in.)	% Change	Average (in.)	Amount of Change (in.)	% Change
0	5.11	1.11	27.8	5.00	1.00	25.0
4	4.83	.83	20.7	4.94	.94	23.5
8	4.45	.45	11.2	4.53	.53	13.2
12	4.40	.40	10.0	4.11	.11	2.7
16	4.80	.80	20.0	3.82	-.18	-4.5
20	4.61	.61	15.2	3.49	-.51	-12.7
24	4.43	.43	10.7	3.36	-.64	-16.0
28	--	--	--	3.52	-.48	-12.0

TABLE V

THICKNESS DATA ON THREE CHARGE CONFIGURATIONS

4340-1 SPHERICAL CHARGE				
Distance from Apex (in.)	Before Forming (in.)	After Forming (in.)	Amount of Change (in.)	% Change
0	.274	.213	.061	22.2
4	.274	.220	.054	19.7
8	.274	.221	.053	19.3
12	.273	.228	.045	16.5
16	.273	.252	.021	7.7
20	.272	.252	.020	7.3
24	.272	.264	.008	2.9
28	.271	.315	+.044	+16.4

4340-2 PANCAKE CHARGE				
Distance from Apex (in.)	Before Forming (in.)	After Forming (in.)	Amount of Change (in.)	% Change
0	.268	.191	.077	28.8
4	.268	.210	.058	21.6
8	.268	.223	.045	16.5
12	.268	.239	.029	10.8
16	.268	.252	.016	6.0
20	.267	.250	.017	6.4
24	.267	.274	+.007	+2.6
28	.266	.297	+.031	+11.6

4340-3 TORUS CHARGE				
Distance from Apex (in.)	Before Forming (in.)	After Forming (in.)	Amount of Change (in.)	% Change
0	.272	.168	.104	38.2
4	.273	.179	.094	34.4
8	.272	.204	.068	25.0
12	.273	.237	.036	13.2
16	.273	.256	.017	6.2
20	.273	.257	.016	5.9
24	.273	.285	+.012	+4.4
28	.272	.287	+.015	+5.5

TABLE VI

COMPARATIVE ANALYSIS OF 18 PER CENT NICKEL STEEL

United States Steel Versus Allegheny Ludlum

UNITED STATES STEEL

Specification: E.F. Maraging Steel, annealed and descaled, GE NP, pickled and oiled
Vendor furnished analysis *

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	B	Ti	Co	Zr
.02	.03	.005	.005	.09	.11	17.73	.01	4.80	.07	.004	.39	7.40	.01

* Hardness was not furnished by vendor but was checked to be R_C32.

ALLEGHENY LUDLUM STEEL

Specification: Almar 18 Ni, 250 consutrode melt cold rolled sheet, pickled and solution annealed condition, Mill Grade 3321
Vendor furnished analysis *

C	Mn	P	S	Si	Ni	Al	Mo	Zr	Ca	Ti	Co	B
.006	.07	.001	.005	.02	18.04	.14	4.80	.002	.006	.60	7.82	.002

* Vendor furnished hardness R_C 31. Aerojet checked to be R_C 33.5.

TABLE VII

STRAIN DATA FOR .175-INCH THICK MARAGING STEEL TESTS

POSITION FROM APEX (In.)	TEST NO. 1 % CHANGE		TEST NO. 2 % CHANGE		TEST NO. 3 % CHANGE	
	Radial	Tangential	Radial	Tangential	Radial	Tangential
0	6.2	6.2	4.2	12.4	4.2	6.2
1/2	1.0	6.2	6.2	7.8	0	6.2
1	3.1	6.2	3.1	7.8	0	4.8
1-1/2	3.1	4.6	0	4.8	3.1	3.1
2	6.2	0	6.2	6.2	6.2	0
2-1/2	8.2	0	9.2	3.1	11.0	0
3	7.2	0	8.2	0	12.4	6.2
3-1/2	0	0	2.0	3.1	9.2	6.2
4	0	0	0	6.2	8.2	7.8
4-1/2	--	--	--	0	--	6.2
Overall Avg.	4.0	2.6	4.5	5.1	6.0	4.7

POSITION FROM APEX (in.)	TEST NO. 1 % CHANGE		TEST NO. 2 % CHANGE		TEST NO. 3 % CHANGE	
	Radial	Tangential	Radial	Tangential	Radial	Tangential
0	8.2	6.2	6.2	9.2	12.4	12.4
1/2	2.0	6.2	5.2	6.2	9.2	12.4
1	4.0	6.2	0	6.2	6.2	6.2
1-1/2	6.2	3.1	6.2	6.2	2.4	4.2
2	8.2	0	6.2	3.1	4.8	0
2-1/2	12.4	0	12.4	0	12.4	0
3	14.6	6.2	11.4	3.1	12.4	6.2
3-1/2	14.6	14.2	5.2	12.4	2.0	6.2
4	--	15.6	3.1	15.6	0	4.2
4-1/2	--	--	3.1	12.4	1.2	4.2
5	--	--	--	12.4	--	--
Overall Avg.	8.8	6.5	6.9	7.9	5.3	5.6

TABLE VIII

THICKNESS DATA ON 0.175-INCH THICK MARAGING STEEL - TESTS NO. 4 AND NO. 5

TEST NO. 4				
Distance from Apex (in.)	Average Before Firing (in.)	Average After Firing (in.)	Amount of Change (in.)	% Change
0	.176	.152	.024	13.6
1/2	.176	.156	.020	11.4
1	.175	.159	.016	9.1
1-1/2	.175	.163	.012	6.9
2	.175	.166	.009	5.1
2-1/2	.176	.167	.009	5.1
3	.175	.170	.005	2.9
3-1/2	.176	.175	.001	.6
4	.176	.180	+.004	+2.3
4-1/2	.177	.190	+.013	+7.4

TEST NO. 5				
Distance from Apex (in.)	Average Before Firing (in.)	Average After Firing (in.)	Amount of Change (in.)	% Change
0	.175	.149	.026	14.9
1/2	.174	.156	.018	10.3
1	.174	.162	.012	6.9
1-1/2	.173	.165	.008	4.6
2	.174	.168	.006	3.4
2-1/2	.174	.169	.005	2.9
3	.174	.169	.005	2.9
3-1/2	.175	.174	.001	.6
4	.175	.183	+.008	+4.6
4-1/2	.175	.188	+.013	+7.4
5	.175	.189	+.014	+8.0

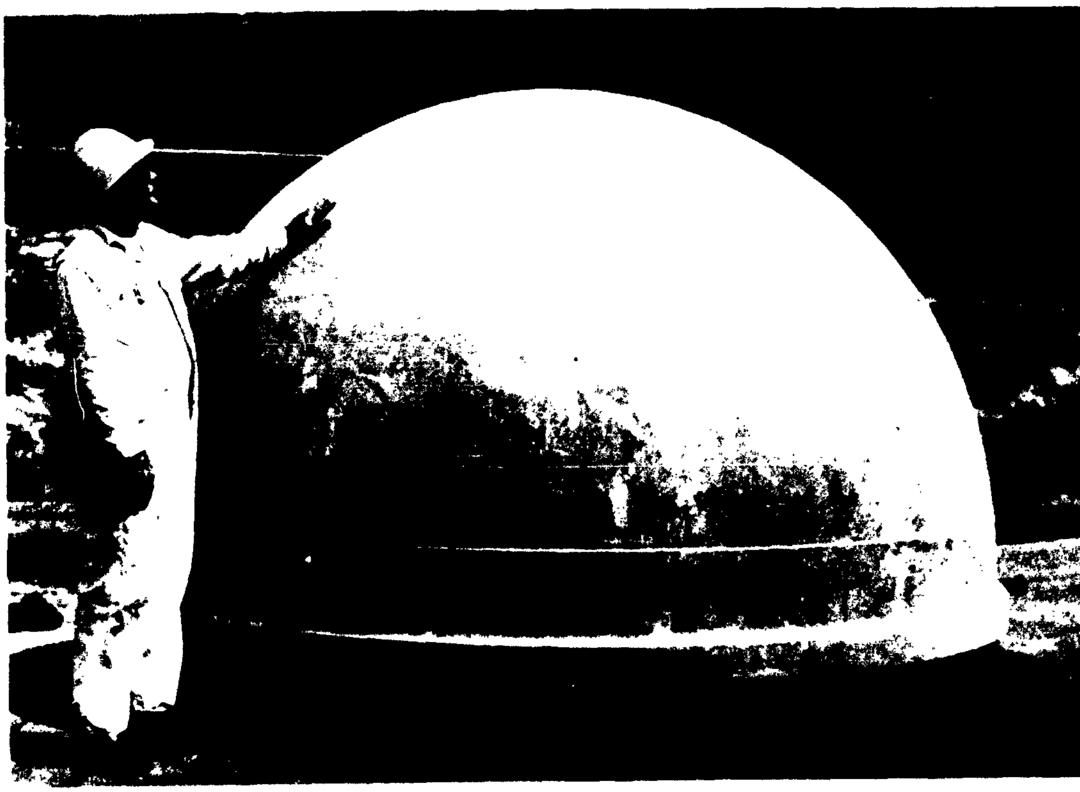


Figure 1. Full Scale Hemispherical Plaster Mold Covered with 3 Layers of Glass Cloth and Plastic Resin

Figure 2. 36-inch Free Forming Die Fabricated of 4130 Steel

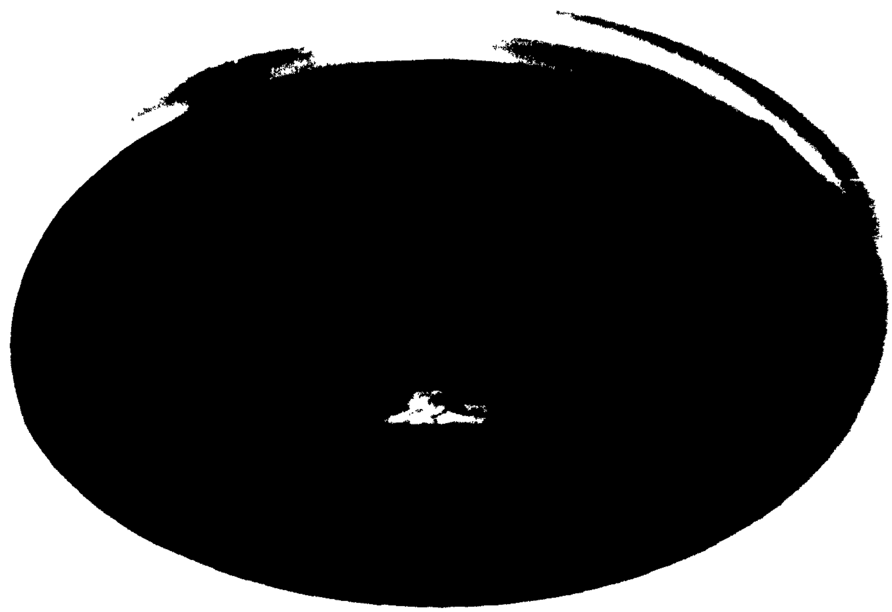


Figure 3. 36-inch Free Forming Die Showing Draw Radius and Die Cavity

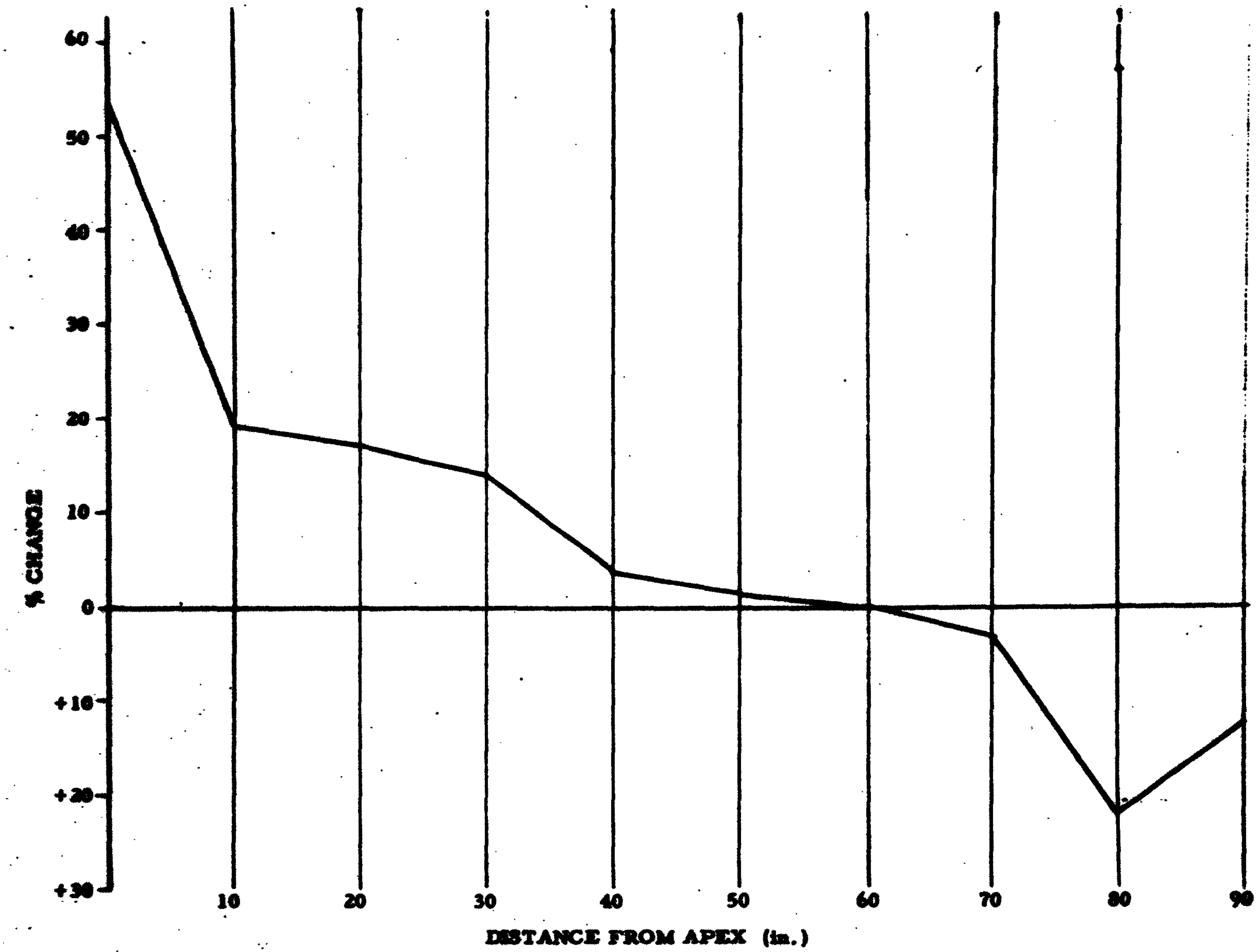


Figure 4. Thickness Change for 120-inch diameter Full Scale Firing, F-4

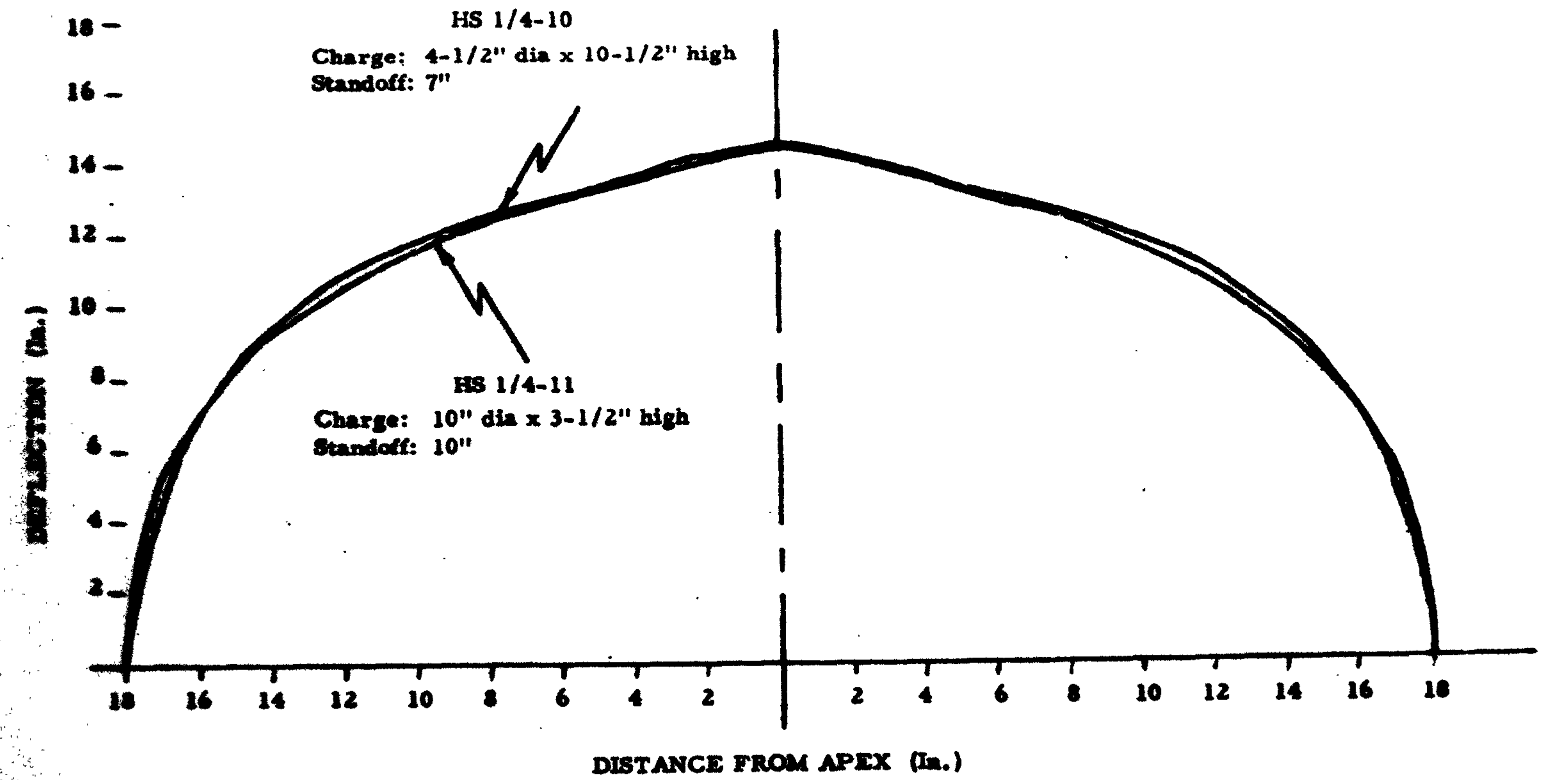


Figure 5. Comparison of Contour Obtained from Cylindrical and Disc Charge Shapes

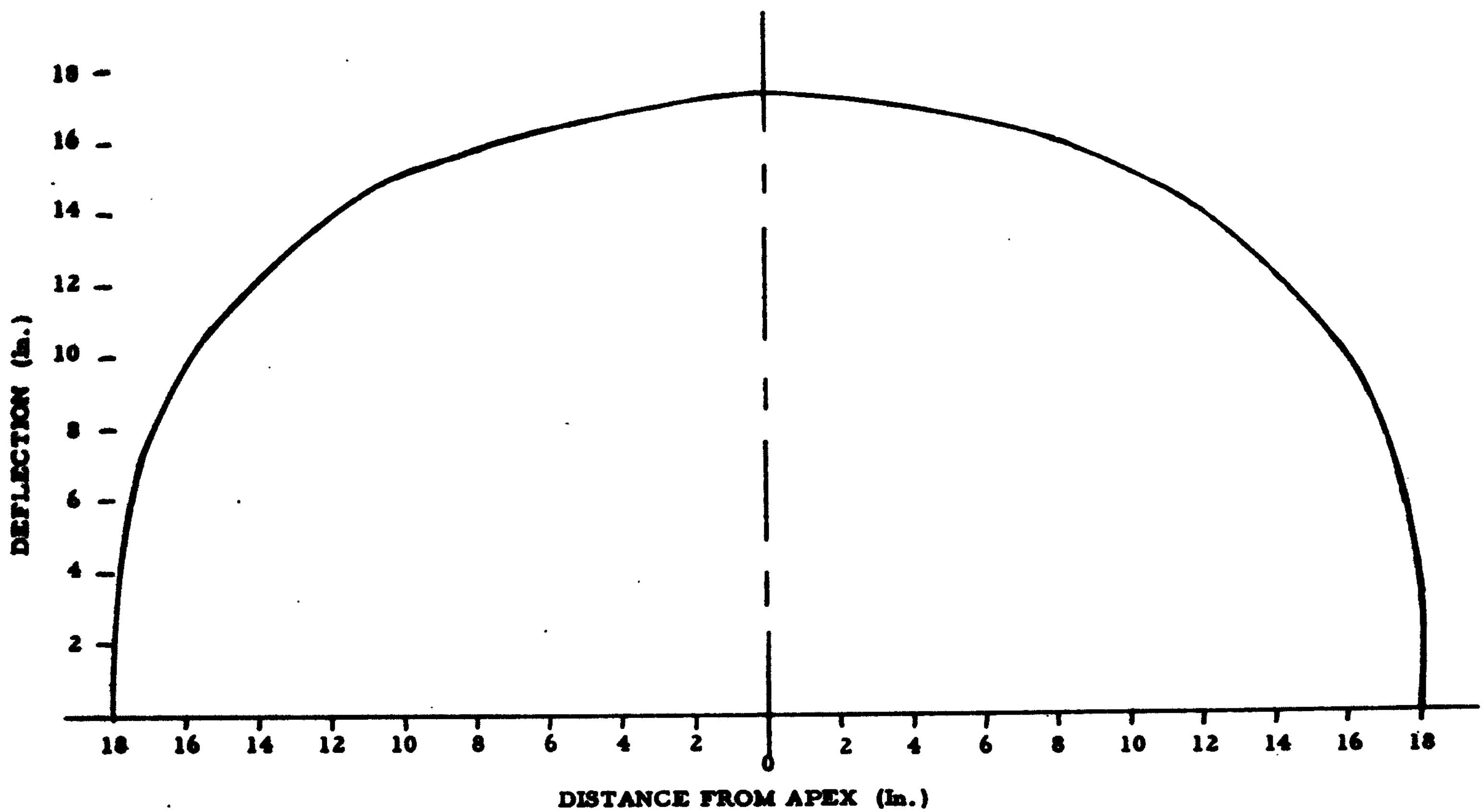


Figure 6. Closure HS 1/4-12.
Contour Obtained with Pancake Charge

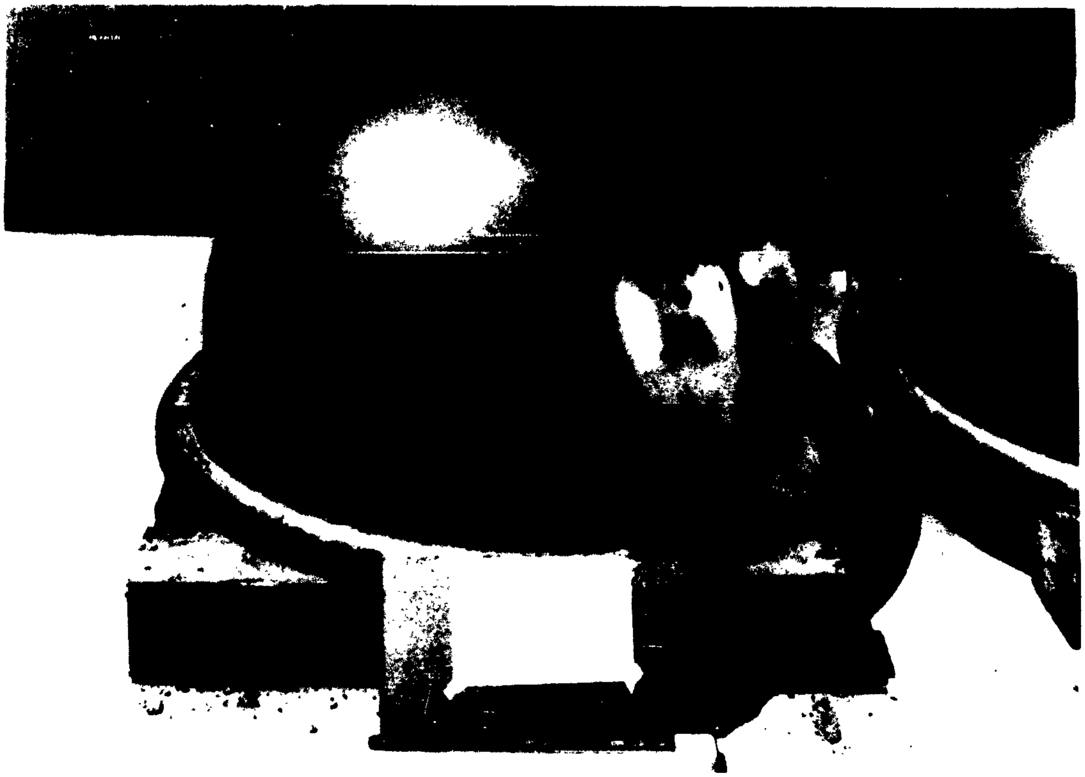


Figure 7. Closure Free Formed with Spherical Explosive Charge

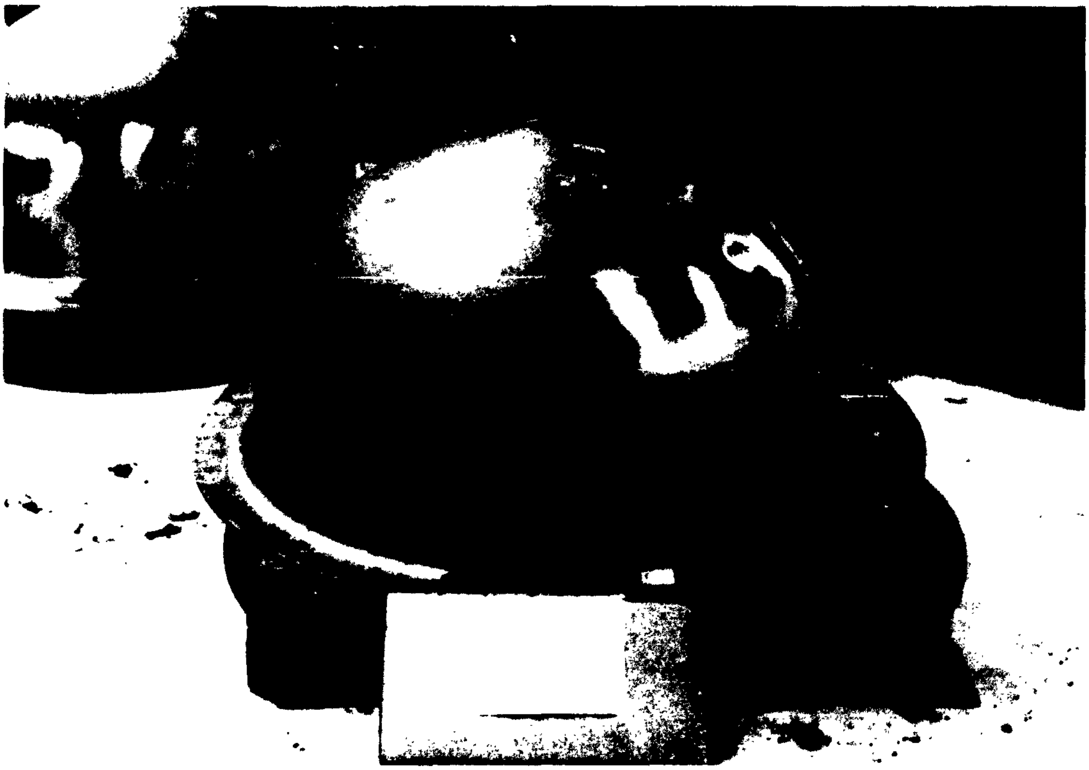


Figure 8. Closure Free Formed with a Right Cylinder Explosive Charge (Pancake), 18-inch diameter x 1/2-inch deep

Figure 9. Closure Free Formed with a 1.5-inch diameter Circular Explosive Charge Rolled into a 27-inch diameter Torus

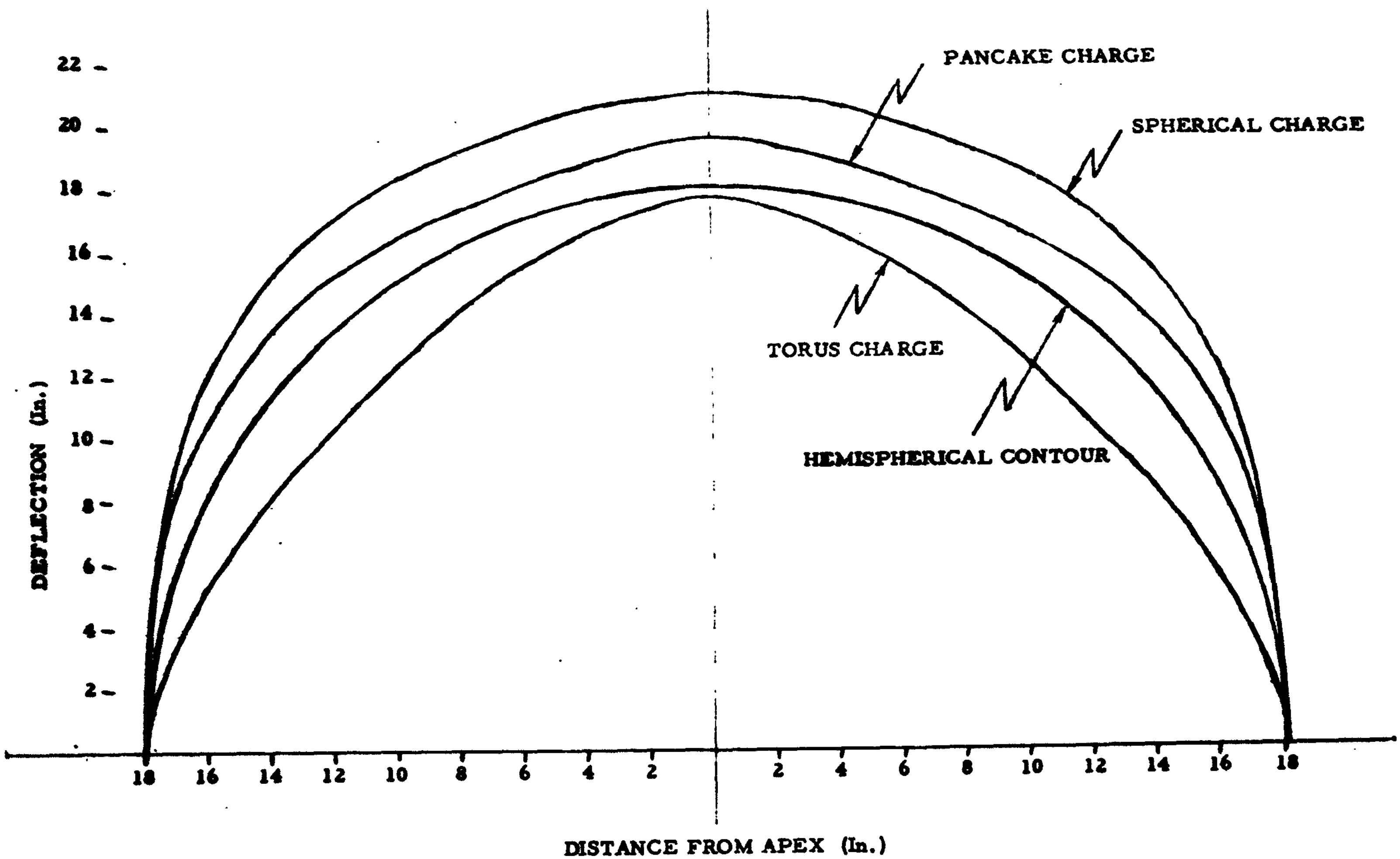


Figure 10. Effect of Charge Shape on Contour Using Free-Forming Die

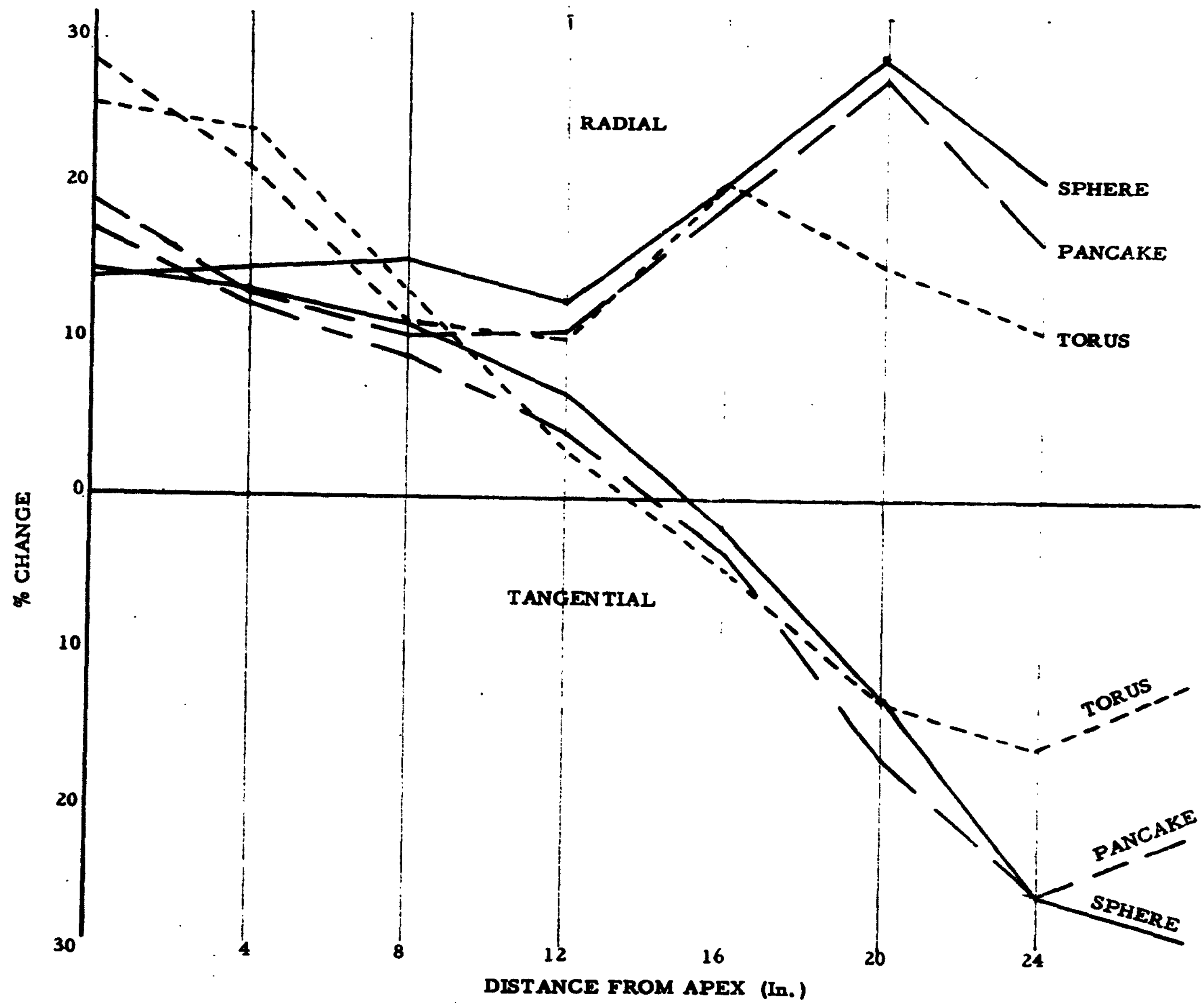


Figure 11. Strain Measurements for Three Charge Configurations

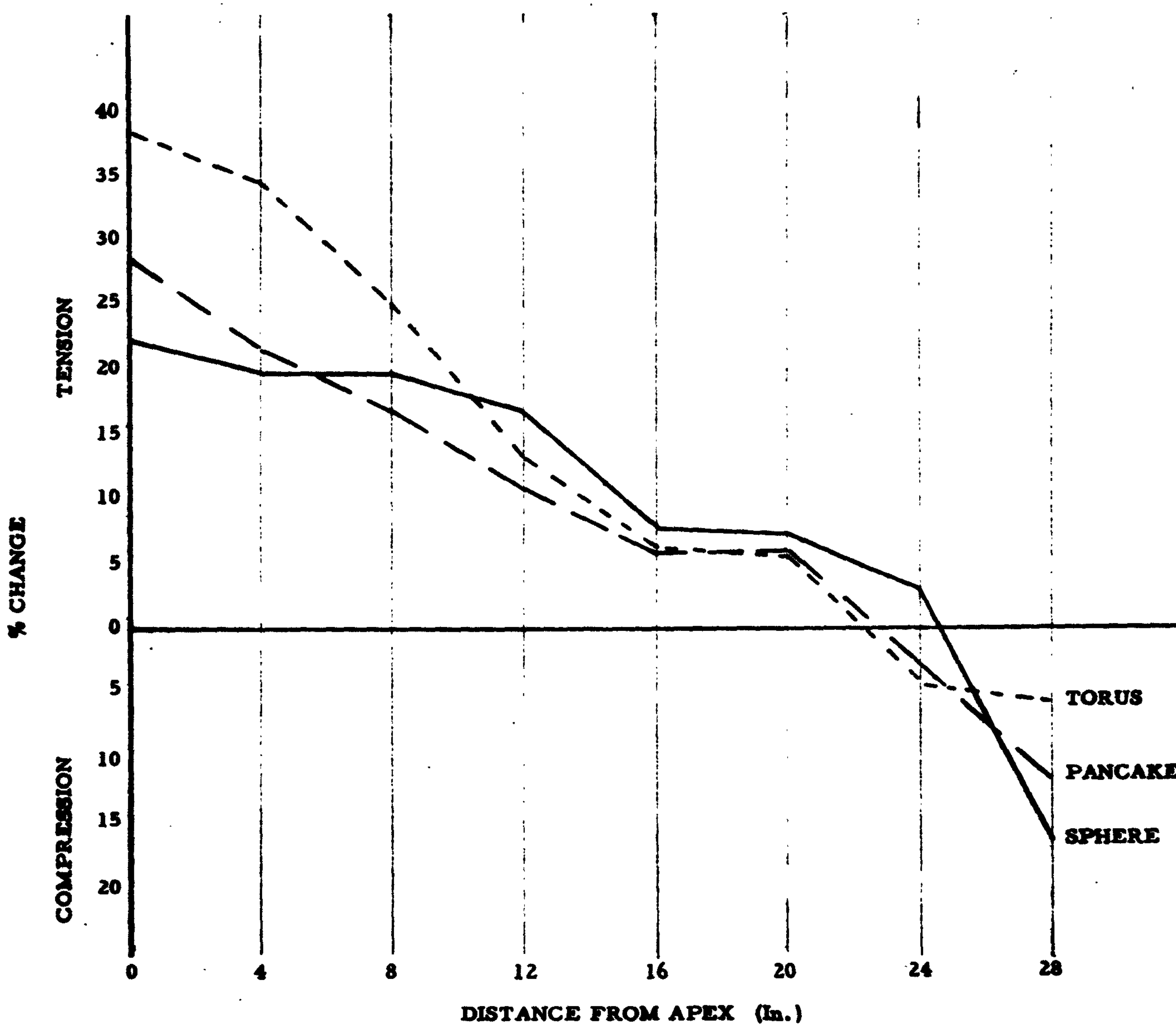


Figure 12. Thickness Change (%) for Three Charge Configurations

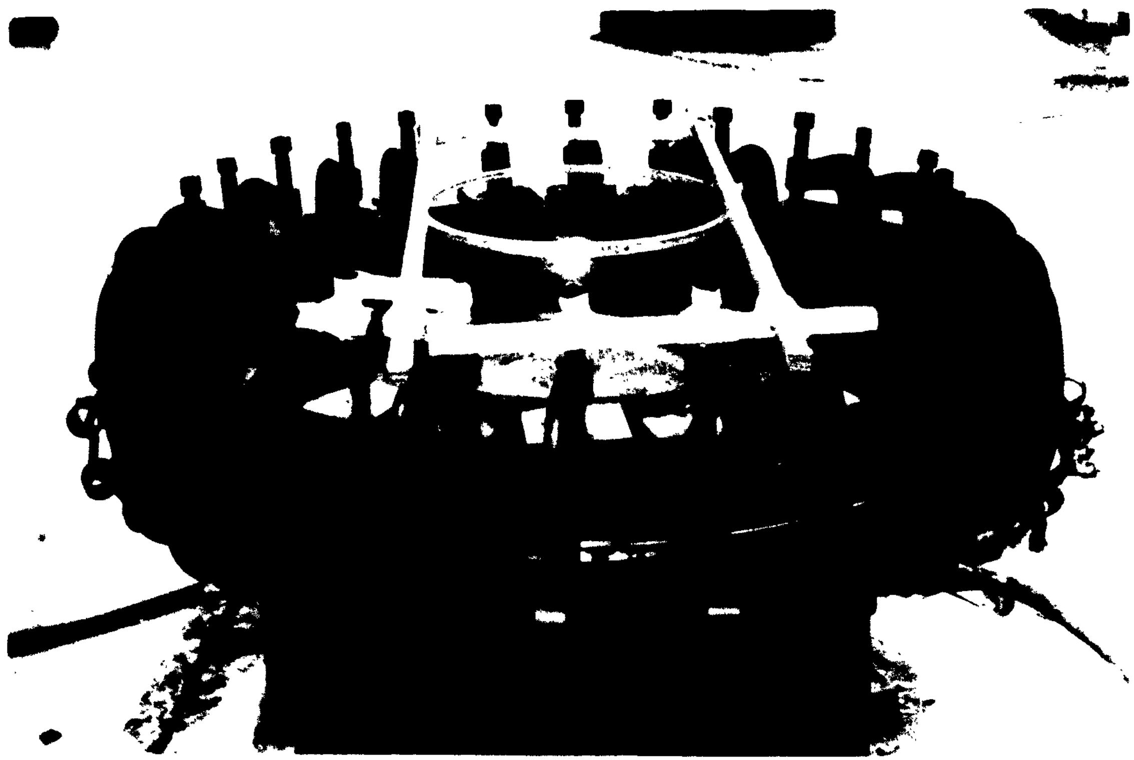


Figure 13. Torus Charge Standoff Assembly Prior to Placing the Charge

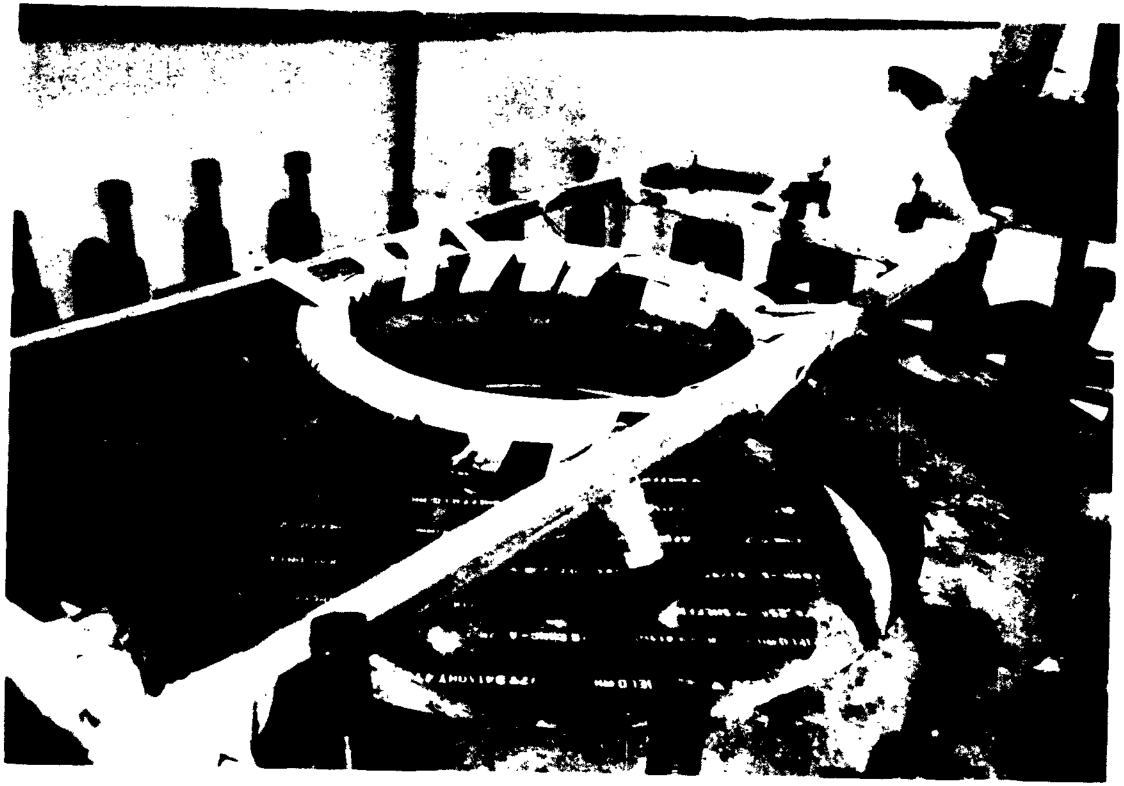
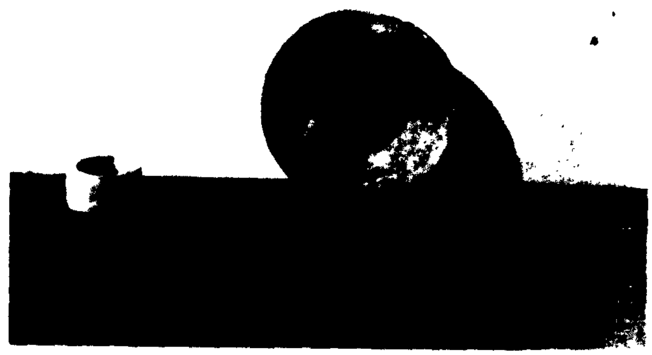
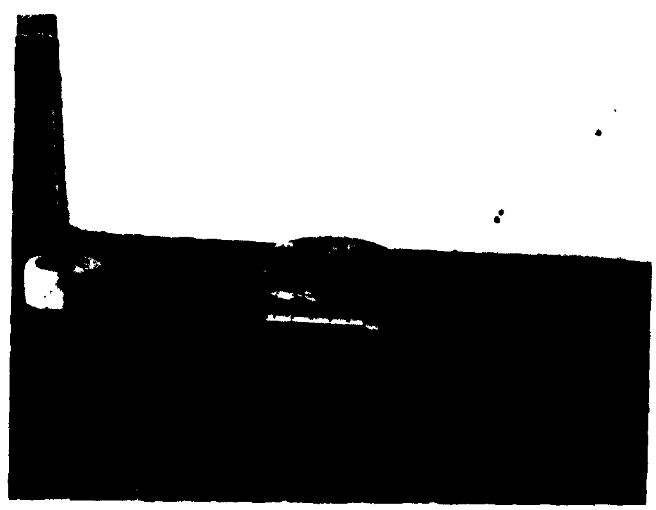


Figure 14. Complete Torus Charge Assembly Prior to Testing

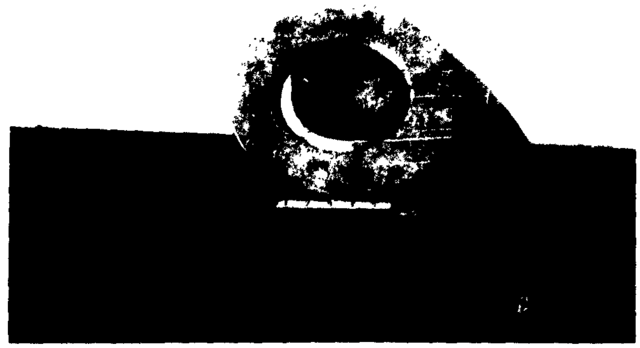


Face View

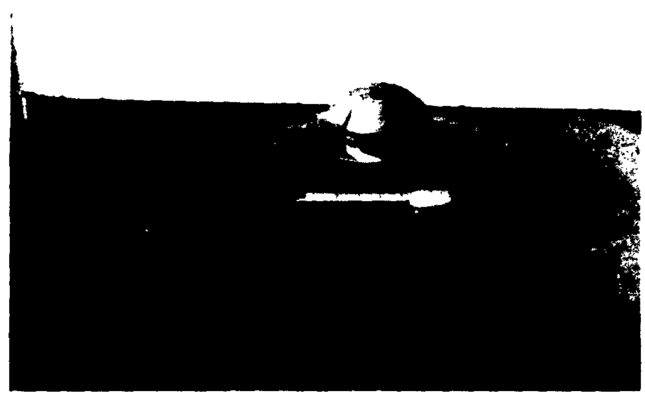


Side View

Figure 15. 18% Nickel Maraging Steel, 3/8-inch thick x 11-inch diameter formed in a 13-inch diameter Contoured Steel Die



Face View



Side View

Figure 16. 18% Nickel Maraging Steel, 3/8-inch thick, formed in a 6-inch diameter Contoured Steel Die

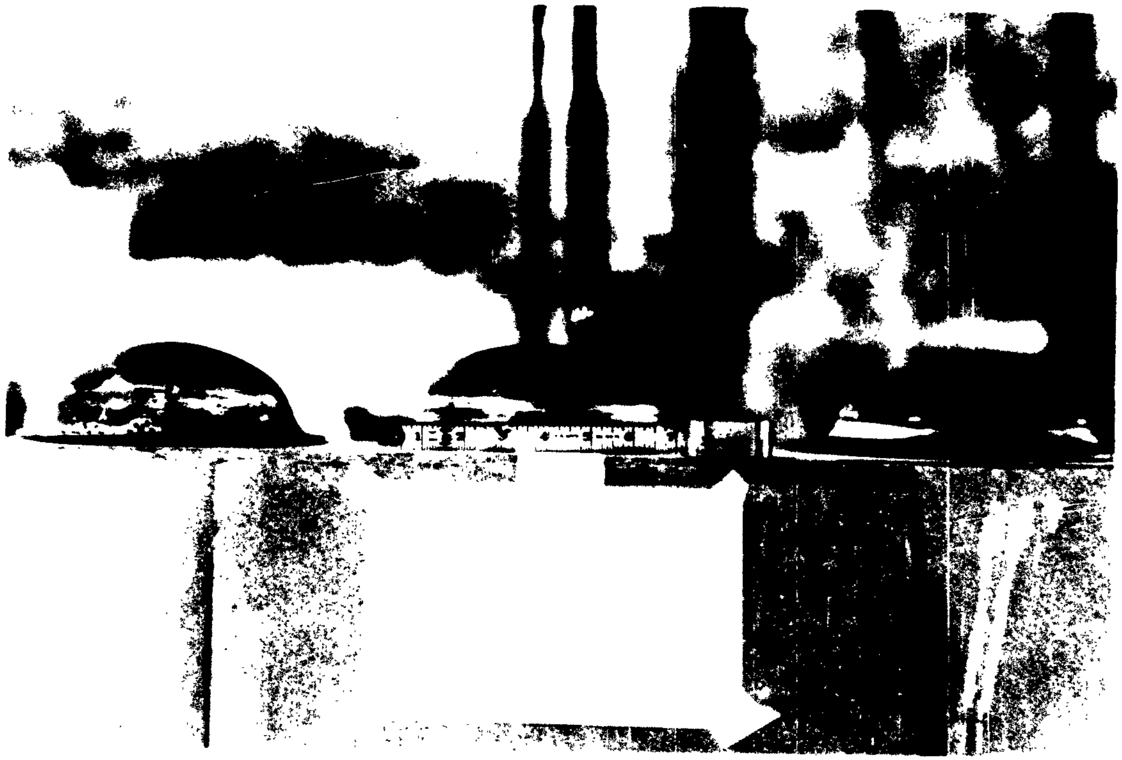


Figure 17. Side View of Explosively Formed 6-inch diameter 18% Nickel M[illegible]ng Steel Domes, 0.175-inch thick

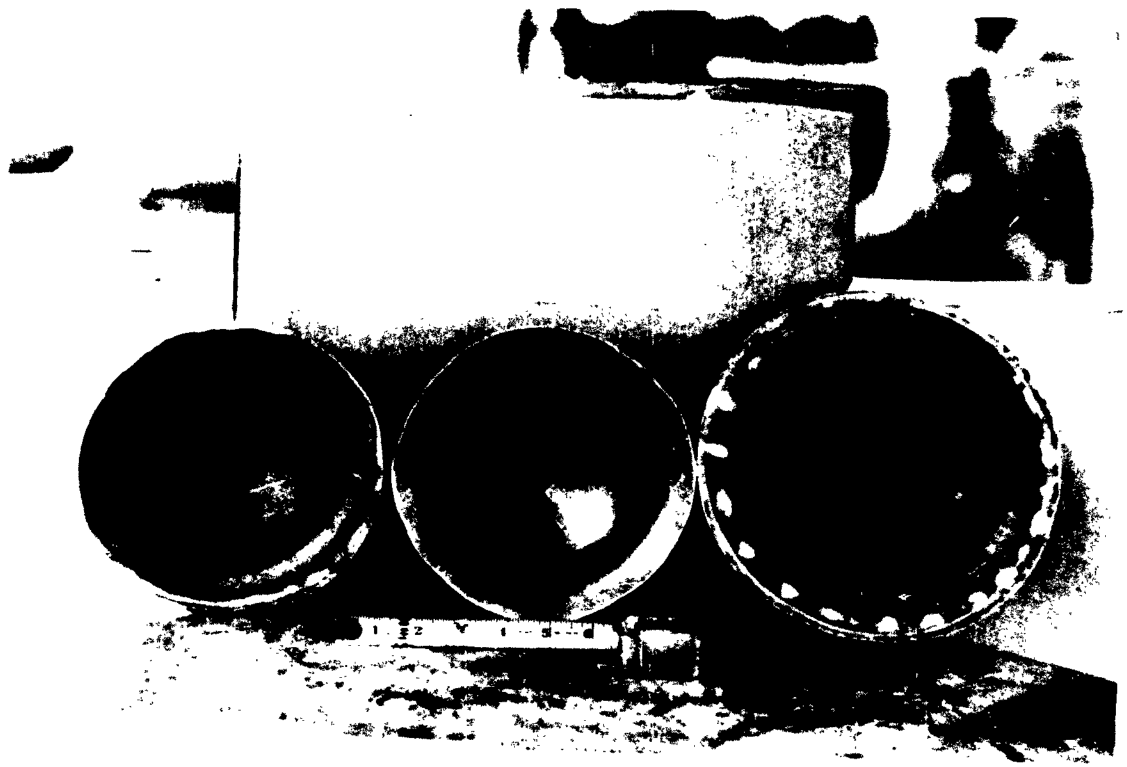


Figure 18. Face View of Explosively Formed 6-inch diameter 18% Nickel Maraging Steel Domes, 0.175-inch thick

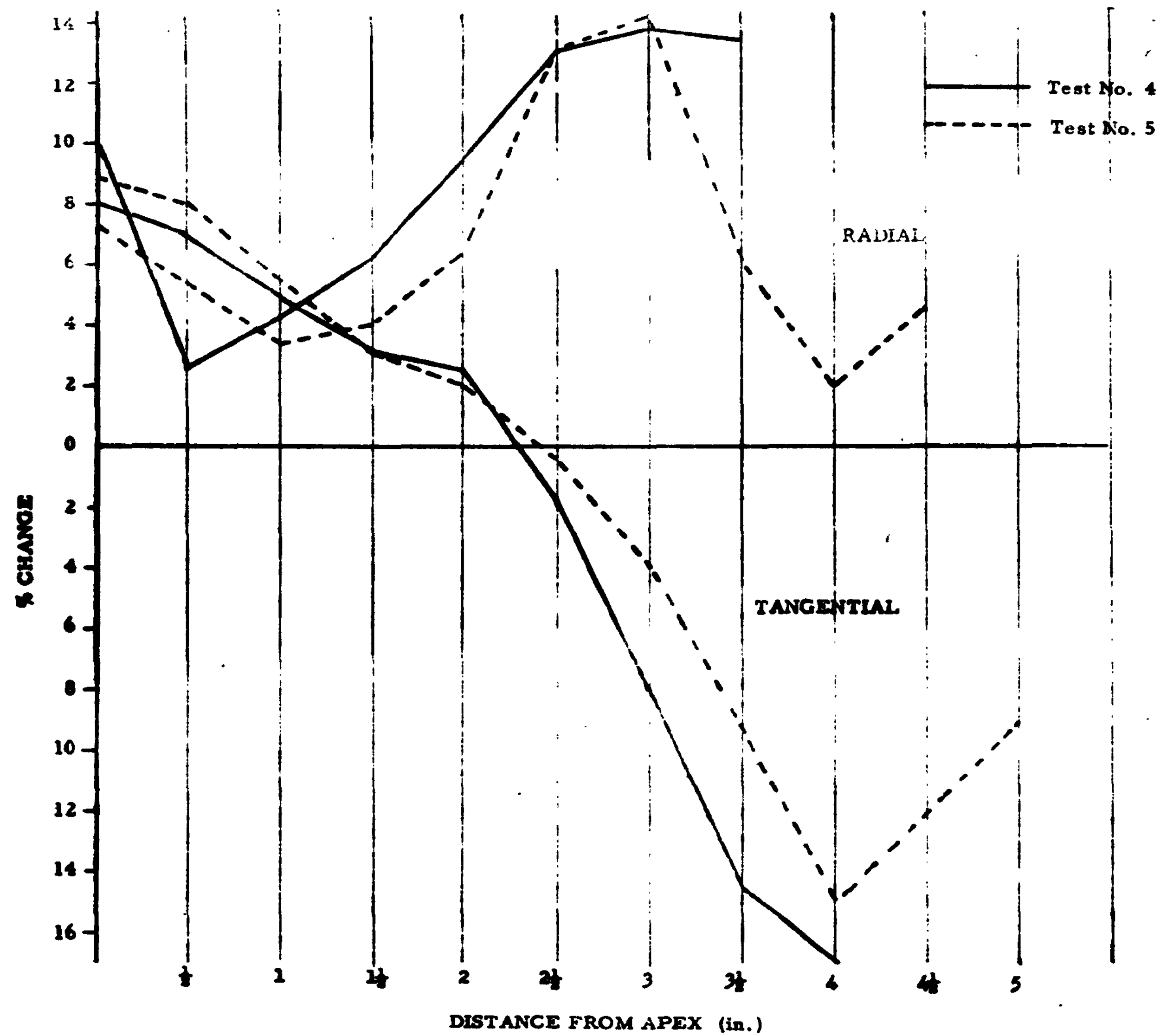


Figure 19. Strain Measurements for Maraging Steel

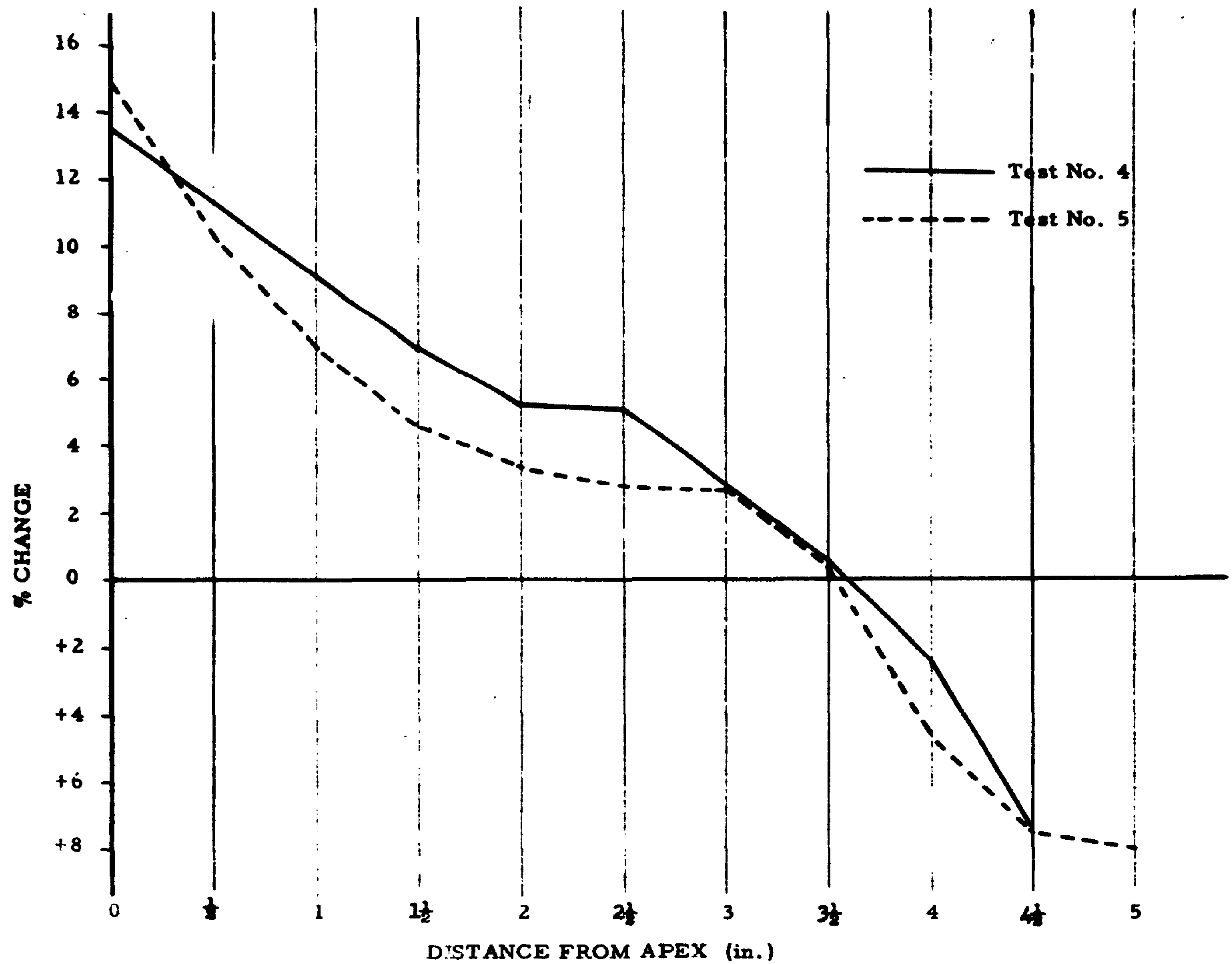


Figure 20. Thickness Change in Maraging Steel (Plotted from Table VIII)

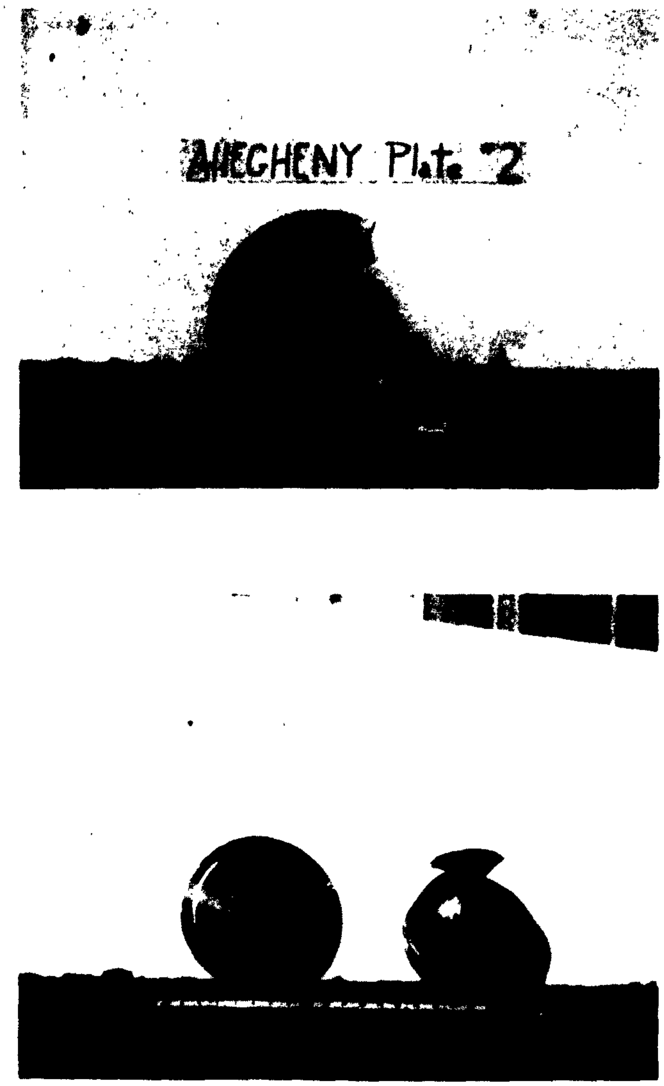
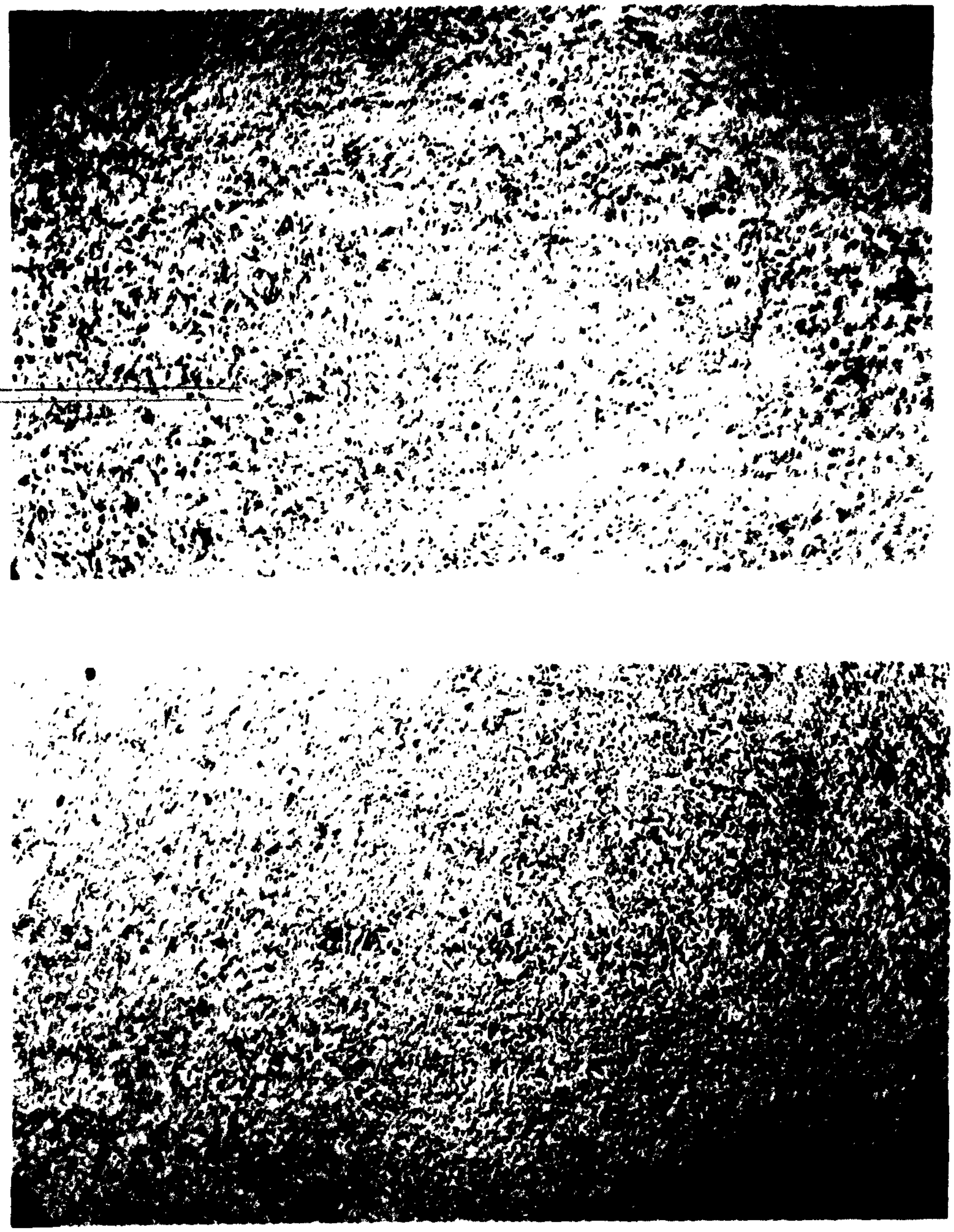


Figure 21. Tests No. 2 and No. 6 illustrate random orientation in 18% Nickel Maraging Steel



A

B

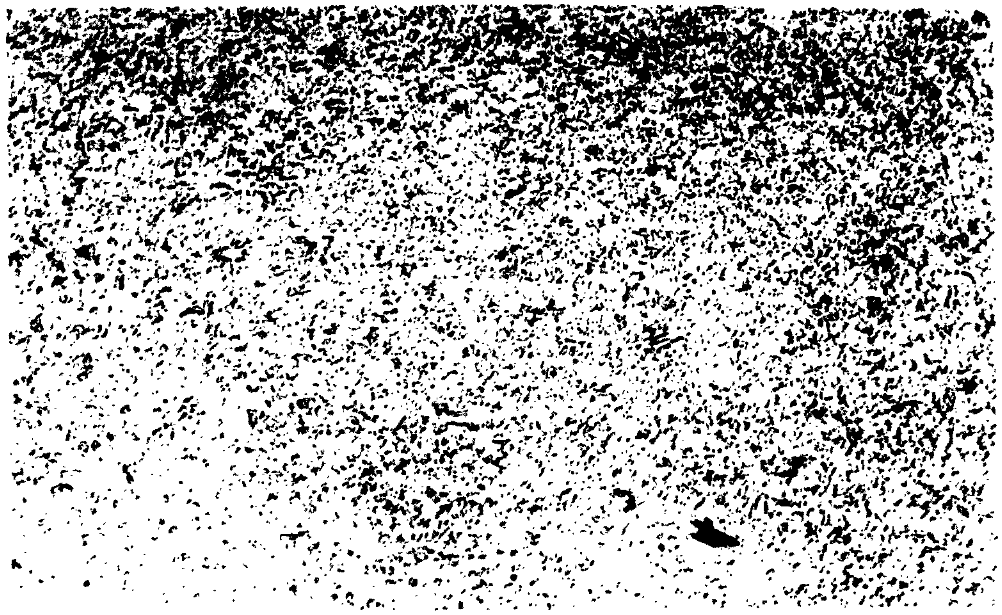
500X

Figure 22. ALLEGHENY LUDLUM 18% NICKEL STEEL (AS-RECEIVED)

(A) Transverse

(B) Longitudinal

MARBLE'S ETCH



A

B

500X

Figure 23. ALLEGHENY LUDLUM 18% NICKEL STEEL (Dome 6)

(A) Transverse

(B) Longitudinal

MARBLE'S ETCH

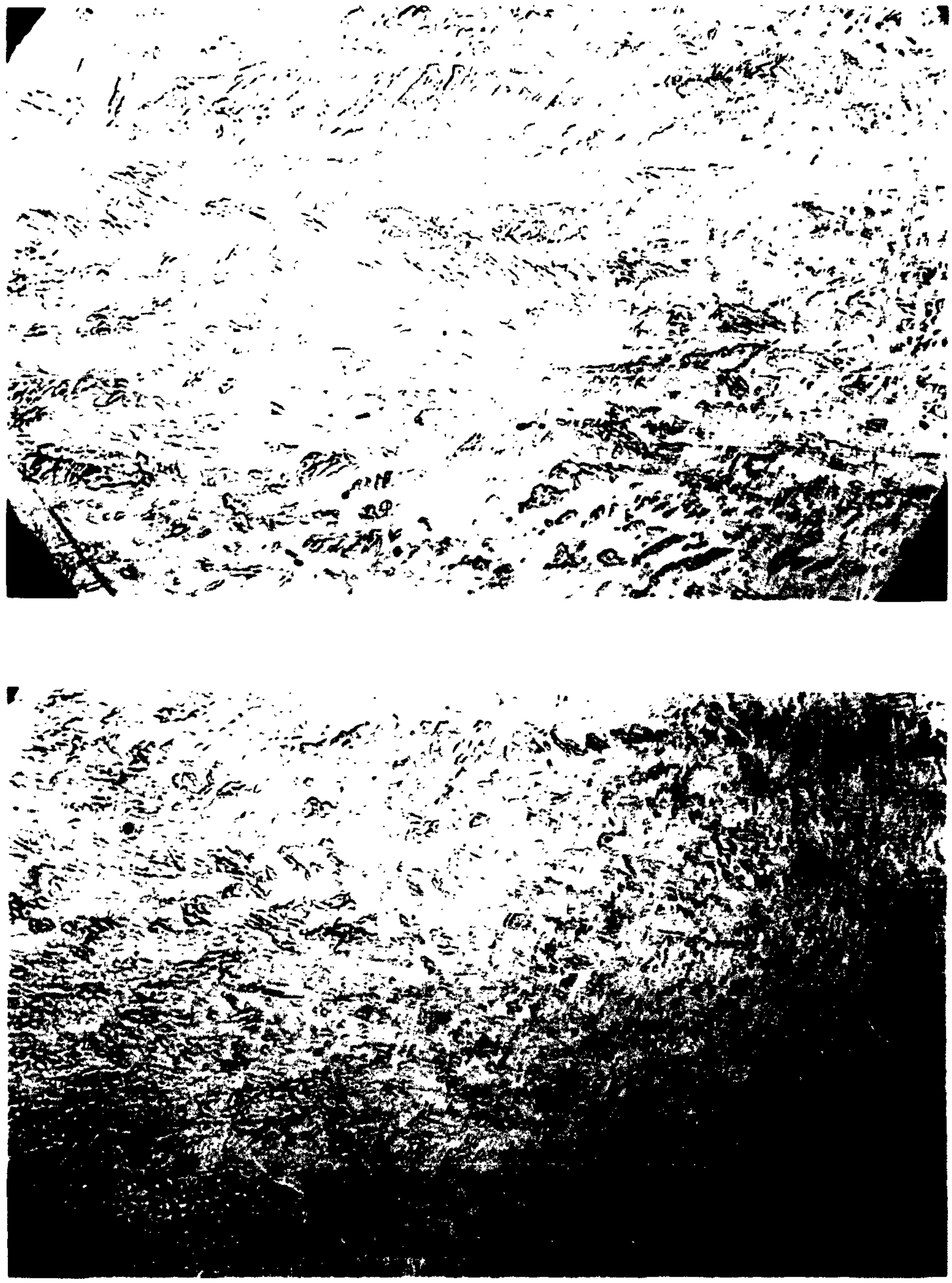


Figure 24. UNITED STATES STEEL 18% NICKEL STEEL (AS-RECEIVED)

(A) Transverse

(B) Longitudinal

MARBLE'S ETCH

A

B

500X

Figure 25. UNITED STATES STEEL 18% NICKEL STEEL (Dome 5)

(A) Transverse
(B) Longitudinal

MARBLE'S ETCH

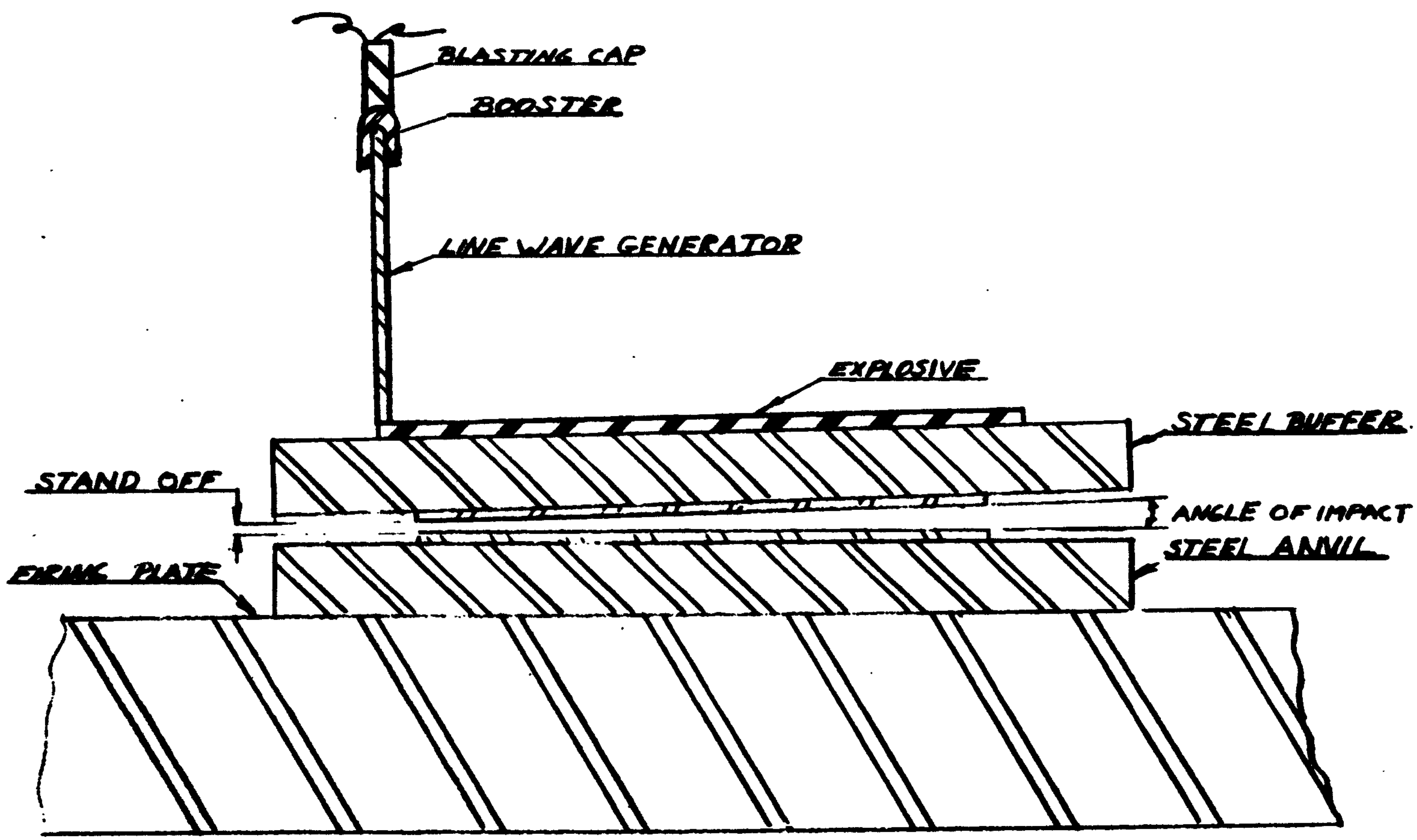


Figure 26. Explosive Weld Test Assembly with Angle of Impact

← Weld Interface

250X

← Weld Interface

500X

Figure 27. EXPLOSIVELY WELDED ALLEGHENY LUDLUM 18% NICKEL STEEL

MODIFIED MARBLE'S ETCH

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